Where words meet numbers

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Title: Where words meet numbers: comprehension of measurement unit terms in posterior cortical atrophy

Authors: Aida Suárez González[a,b], Paul Hoffman[c,d] and Sebastian Crutch[a]

Affiliations:

a. Dementia Research Centre, Department of Neurodegenerative Disease, UCL Institute of Neurology, University College London, London, United Kingdom.
b. Memory Disorders Unit, Department of Neurology, University Hospital Virgen del Rocío, Seville, Spain.
c. Neuroscience and Aphasia Research Unit, School of Psychological Sciences, University of Manchester, Manchester M13 9PL, United Kingdom
d. School of Philosophy, Psychology & Language Sciences, University of Edinburgh, Edinburgh EH8 9JZ, United Kingdom

Author for correspondence: Sebastian Crutch. Dementia Research Centre, Box 16, National Hospital for Neurology and Neurosurgery, Queen Square, London, WC1N 3BG, UK. E-mail: s.crutch@ucl.ac.uk

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Abstract

Units of measurement (e.g., metre, week, gram) are critically important concepts in everyday life. Little is known about how knowledge of units is represented in the brain or how this relates to other forms of semantic knowledge. As unit terms are intimately connected with numerical quantity, we might expect knowledge for these concepts to be supported by parietally-mediated representations of space, time and magnitude. We investigated knowledge for measurement units in patients with posterior cortical atrophy (PCA), who display profound impairments of spatial and numerical cognition associated with occipital and parietal lobe atrophy. Relative to healthy controls, PCA patients displayed impairments for a range of unit-based knowledge, including the ability to specify the dimension which a unit refers to (e.g., grams measure mass), to select the appropriate units to measure everyday quantities (grams for sugar) and to determine the relative magnitudes of different unit terms (gram is smaller than kilogram). In most cases, their performance was also significantly poorer than a patient control group diagnosed with typical Alzheimer's disease. Our results suggest that impairment to systems that code numerical and spatial magnitudes has an effect on non-numerical verbal knowledge for measurement units. Units of measurement appear to lie at the intersection of the brain's verbal and numerical semantic systems, making them a critical class of concepts in which to investigate how magnitude-based codes contribute to verbal semantic representation.

Keywords: Posterior cortical atrophy, semantic memory, units of measurement, magnitude

1. Introduction

A widely supported dissociation in neuropsychology is that between numerical cognition and non-numerical semantic memory (Pesenti, 2000; Thioux et al., 1998; 2005; Cipolotti et al., 1991). This position is supported in part by a large literature showing relatively preserved number knowledge in patients with semantic dementia (SD) who exhibit profound and pervasive impairments in other domains of conceptual knowledge (e.g. Cappelletti et al., 2001, 2005, 2012; Crutch and Warrington, 2001, 2002; Diesfeldt, 1993; Jefferies et al., 2005; Kopelman, 2001; Lemer et al., 2003; Rossor et al., 1995; Zamarian et al., 2006). Conversely, patients with parietal damage in the context of stroke or posterior cortical atrophy exhibit impaired knowledge in the domain of numerical cognition but good semantic memory in other domains (Dehaene & Cohen, 1997; Delazer, Karner, Zamarian, Donnemiller, & Benke, 2006; Kas et al., 2011). These findings suggest a neural dissociation between parietal lobe systems that support numerical knowledge (potentially along with representation of non-numerical magnitudes; see Cohen Kadosh, Lammertyn, & Izard, 2008) and anterior temporal cortex (the focus of damage in semantic dementia; Nestor et al., 2006) that supports other forms of conceptual knowledge (Patterson et al., 2007). There is also evidence for interaction between these two systems. For example, despite SD patients' impressive preservation of a range of number transcoding and calculation skills, such patients do exhibit impairments on some tasks tapping quantity knowledge such as placing numbers on an analogue scale and estimating height, weight and age in conceptual contexts (Julien et al., 2010). These studies all examine comprehension of numbers (which explicitly label specific quantities) or quantity facts (knowledge about specific quantities associated with given objects or situations). However, to date there have been no examinations of the semantic and numerical status of words lying at the interface between these two systems, namely measurement unit terms (e.g. kilogram, centimetre, hour, centigrade).

A unit of measurement is a definite magnitude of a physical quantity, defined and adopted by convention or by law that is used as a standard for measurement of the same physical quantity (Joint

Committee for Guides in Metrology, 2008). As indicated by this definition, unit terms are frequently used in association with number terms (multiples) to define specific quantities (e.g. the 100 metre world record is 9.58 seconds) and can themselves be defined in terms of specific quantities of other units (e.g. a metre is 100 centimetres). However, unit terms, unlike numbers, are open-class words and can also be used without explicit reference to specific quantities (e.g. one can know that "metre" is a measuring word, but not necessarily which dimension or what specific quantity it refers to).

Like other types of concept, semantic representations of unit terms comprise information at varying levels of specificity. In patients with semantic dementia, for example, gradual erosion of the semantic network yields situations in which specific subordinate information about both concrete and abstract concepts is lost (e.g. concrete example: a camel has humps and spits; abstract example: brusque means blunt rather than crude) whilst more general superordinate information may be spared (e.g. a camel is an animal; brusque is a negative quality; see Warrington, 1975; Hodges et al., 1995; Crutch and Warrington, 2006). Similarly, for a unit of measurement such as 'kilogram', one could place statements of information about the concept in a putative order of (increasing) magnitude specificity, e.g. A kilogram is:

- a 'measuring' word
- something to do with weight (and not time, distance, etc.)
- a moderate weight (less than a tonne, more than a gram)
- commonly used to describe the weight of flour, body weight, etc. (and not ships, herbs in recipes, etc.)
- 1 kg = 1000g = 0.001 tonnes etc.

In summary, unit terms may occupy a theoretically informative middle ground between numerical and non-numerical semantic systems. Our knowledge of them includes a variety of semantic and verbal associations with words and objects, generally thought to be coded in anterior temporal regions. At the same time, their intimate connection with quantity and number suggests that knowledge for these concepts may be highly dependent on parietal cortex. In this study we investigate the semantic status of unit of measurement terms in individuals with prominent parietal degeneration, namely posterior cortical atrophy (PCA). PCA is the most common atypical AD phenotype (Dubois et al., 2014) and is a clinicoradiological syndrome characterized by progressive degradation of visual processing and other posterior cognitive functions associated with prominent parietal, occipital and occipito-temporal atrophy (Crutch et al., 2012). Unsurprisingly, previous clinical, neuropsychological, brain-behaviour and clinical impact studies have tended to focus upon the cardinal cognitive deficits laid out in the available diagnostic criteria (Mendez et al., 2002; Tang-Wai et al., 2004): namely impairments in object and space perception and attention, numeracy, literacy and praxis. Whilst impairments on standard calculation tests of addition and subtraction have been documented in a number of group studies (e.g. McMonagle et al., 2006; Kas et al., 2011; Lehmann et al., 2011), we are only aware of one previous detailed investigation of calculation skills in PCA (Delazer et al., 2006). This single case study of patient HR revealed profound impairments on complex calculation and number sequencing tasks. However, in spite of strong non-numerical conceptual knowledge (semantic definition, association and categorisation), HR also performed poorly on tests of conceptual knowledge of arithmetic principles, encyclopaedic number knowledge and everyday number facts. We have noted similar impairments in semantic quantity facts for even highly familiar entities (e.g. How many days in a week? “Six”; How many cents are there in a euro? “Ten”; Crutch et al., unpublished).

In addition to explicit numerical tasks, PCA patients also appear to have difficulties on tasks involving the implicit appreciation and comparison of magnitude information (e.g. cognitive estimation tasks). Certain types of errors on cognitive estimation tasks are unsurprising given the numerical knowledge deficits outlined above. For example, PCA patients make errors on tasks owing to gross mis-estimation of the quantities involved (e.g. What is the height of the Post Office tower? “30 feet”;

What is the age of the oldest person in Britain today? “150” [responses of a patient with MMSE 24/30]). However, other responses to cognitive estimation questions hint at a fundamental problem in understanding and using not only numbers but also the measurement unit terms which often accompany them (e.g. How fast does a horse gallop? “12 whatever the unit is, per mile? Per hour? …”). Some of these unit term errors, especially omission errors (e.g. What is the population of Britain today? “500… [no unit given, in a patient with MMSE 24/30]”) or substitution errors (How fast do race horses gallop? “12 minutes” [in a patient with MMSE 26/30]) might be attributable to word retrieval impairments (see Crutch et al., 2013 for evidence for language impairments in PCA). Other comments from participants though have led us to examine a conceptual rather than retrieval basis for these unit of measurement errors. For example, we asked one patient “What is the length of an average man’s spine?”. Crutch et al., unpublished). He replied, “9 whatever the unit is. If you want it in centimetres I don’t know it. [Have a guess] 10? That’s what catches me, the unit. I keep bouncing between different units”. This same individual, when asked to define unit terms and their use also made a small number of intriguing errors (e.g. What unit would you use to measure medicine to be injected? “Gallons”) which suggest partial knowledge of certain measurement unit terms (knowing the dimension it refers to but not the exact magnitude).It was these apparent partial knowledge errors which influenced the design of tasks in the present investigation.

The current study examined comprehension of measurement unit terms in individuals with PCA, a patient control group of individuals with typical Alzheimer’s disease (tAD) and a group of healthy controls. Parietal lobes show a more severe atrophy in PCA compared to tAD, while tAD is characterised by a more severe atrophy involving the medial temporal lobe (Lehmann et al., 2011). It seems that there is also a trend towards this dissociation when looking at classical semantic structures, the anterior temporal lobe for semantic knowledge and the inferior parietal cortex for numerical semantic knowledge (Lehmann et al., 2011). Thus, differences in performance in these two patient groups may play as a model to help elucidate the underpinning role of the parietal lobe in magnitude knowledge, this is, the interplay where verbal and numerical knowledge meet. Participants completed a linked series of four multi-component experiments tapping verbal knowledge of unit terms ranging from categorisation and association to (non-numerical) magnitude estimation. The experiments were ordered according to an a priori, hypothetical grading of the specificity (numerosity) of information required to complete each task (see putative hierarchy for the term ‘kilogram’ above). The tasks explored whether participants knew that a target term was a unit of measurement (Experiment 1), the dimension of measurement to which the unit refers (Experiment 2), the type of entities/substances which might be measured with that unit (Experiment 3), and the approximate magnitude of that unit (without obligatory recourse to specific enumeration; Experiment 4). Thus, whilst other studies of quantity processing in PCA have focussed on the relationship between numerical and spatial representations (Delazer et al., 2006), here we focus on the relationship between numerical and verbal semantic representations. It was hypothesised that PCA patients, with pronounced parietal but limited anterior temporal lobe atrophy, would show a gradient of performance with impaired magnitude-dependent knowledge but relative sparing of more purely verbal knowledge of measure unit terms. By contrast, the typical AD patient control group, with more comparable temporal and parietal atrophy, were predicted to show a more equivalent pattern of weakening in their magnitude and non-magnitude knowledge for measurement units.

2. Methods

2.1 Participants

The study participants were 8 patients with PCA, 21 with typical AD (tAD) and 18 healthy control subjects (N= 47). The inclusion criteria required that the PCA patients met clinical criteria for a diagnosis of posterior cortical atrophy (Mendez et al., 2002; Tang-Wai et al., 2004). These criteria include insidious and progressive presentation of visual processing deficits in the absence of ocular disease; preserved insight and relatively preserved episodic memory. Supportive features are visual agnosia and simultagnosia, apraxia, environmental disorientation and ocular apraxia and optic ataxia. Both patients with PCA and with typical AD met clinical criteria for probable AD (McKhann et al., 2011) and were diagnosed and recruited at the Memory Disorders Unit of the Hospital Virgen del Rocio (Seville, Southern Spain) during 2013. A diagnosis of typical AD implies that the initial and most prominent cognitive deficit evident both on history and examination is the amnestic presentation, characterised by impairment in learning and recall of recent information plus evidence of dysfunction in at least one of the following: impaired reasoning, visuospatial abilities, language and changes in behaviour. The local Institutional Review Board approved the study protocol and the participants gave informed consent to participate in the study. The control group were significantly younger than the PCA group ($t(24) = 4.89$, $p < 0.001$) and the tAD group ($t(37) = 2.32$, $p = 0.026$). In addition, the tAD group was younger than the PCA group ($t(27) = 3.40$, $p = 0.002$). To control for potential effects of age on our results, all statistical comparisons included age (and disease duration where appropriate) as covariates.

2.2 Background neuropsychology

Participants completed a background neuropsychological battery including the Mini Mental State Examination (MMSE; Folstein et al., 1975), immediate and delayed word list recall and delayed recognition (Wechsler Memory Scale-III; Wechsler, 1997), forwards and backwards digit span and phonemic and semantic fluency. The PCA and tAD patients also completed a test of oral calculation and seven subtests from the Visual Object and Space Perception battery (VOSP; Warrington and James, 1991). The mean and standard deviation scores for each group are shown in Table 1, together with significance values relating to the statistical effect of group (expressed as pairwise comparisons) upon performance. PCA and tAD performance did not differ significantly on any of the episodic memory, short term/working memory or fluency measures. Both groups were impaired relative to controls on all these measures except digit span forwards. By comparison, PCA patients achieved significantly lower scores than tAD patients on the calculation test and on the basic visual processing (Shape detection), object perception (Fragmented letters, Object decision) and space perception (Dot counting, Position discrimination, Number location, Cube analysis) VOSP subtests.

2.3 Experimental tasks

All tasks were administered orally in Spanish, with the experimenter speaking aloud the probe and response options and providing unlimited repetitions of these items if participants asked to hear the question again or had difficulty retaining the stimuli. Examples aiming to clarify the tasks were provided at the beginning of each experiment. For example, in Experiment 1: "Now I'm going to read aloud one word which is a unit and I will ask you to match it with one of two other words. Your matching criteria are that both words must be measurement units. For instance, if the word I give you is *mes* (month), with which one of the following words would you match it, with gramo (*gram*) or with g*aviota* (seagull)?". If the patient failed to provide the right response he was provided with the right choice and an explanation of why their response was incorrect. The combination of items given in the examples differed from those contained in the experimental tasks to avoid facilitation of performance. The original stimuli, both in Spanish and English, can be found in Appendix 1 and 2 respectively (Appendix 3 is a direct translation of the Spanish stimuli into English) .

2.3.1 Experiment 1

This experiment tested the knowledge that a term (e.g kilogram) is a unit of measurement in two different tasks:

1a. Dimension not matched (N=10 trials): To examine superordinate knowledge that target terms belonged to the category of units of measurement, participants were asked to match a target unit term with one of two response words only one of which was also a term of measurement (e.g. week: inch or finch; kilogram: centimetre or centipede). In this task, the probe and target units referred to different dimensions of measurement (e.g. time vs. distance).

1b. Dimension matched (N=10): To create an easier version of Experiment 1a, the procedure was repeated with probe and target units drawn from the same dimension of measurement (e.g. "semana: día or vía"[week: day or way]). As in Experiment 1a, the foils were not measurement terms.

1c. Non-magnitude semantic judgments (person adjectives; N=10): As a control task to ensure performance on Experiments 1a, 1b and subsequent tasks did not merely reflect concomitant deficits in short term memory, verbal comprehension and capacity to understand task instructions or demands, participants were asked to complete a third task involving the judgment of semantic similarity of non-unit terms (e.g., powerful: strong or stupid; boring: dull or full).

2.3.2 Experiment 2

The second experiment probed knowledge of the dimension of measurement to which the unit refers (e.g. a kilogram refers to weight and not distance):

2a. Matching units of same dimension (N=10): Participants were asked to match probe words to other terms "used to measure the same type of thing" (e.g. day: century or milligram).

2b. Matching unit to dimension name (N=10): This task directly addressed participants' knowledge of the dimension to which specific unit terms related (e.g. day: weight or time).

2.3.3 Experiment 3

This experiment investigated the interaction between unit knowledge and knowledge for non-unit concepts by probing the entities that might be measured with a given unit (e.g. kilogram is the typical unit used to weigh flour, bodies, bricks, etc. but would be less natural unit to express the weight of a ship or a coin).

3a. Entity measured with given unit (N=10): Real world use of unit terms was evaluated by asking participants which of two entities might be measured with a given unit of measurement (e.g. "Which would you measure in grams: flour or petrol?).

3b. Unit used to measure given entity (N=10): Experiment 3b was motivated by the performance of a patient in a previous case-series examination of magnitude processing in PCA, who was asked "What units would you use to measure medicine?" and in free response stated "gallons" (correct dimension [volume] but incorrect magnitude; Crutch et al., in prep). Accordingly, participants were asked to provide the best unit to measure various entities under a two alternative forced choice procedure (e.g. truck: tons or grams).

2.3.4 Experiment 4

Experiment 4 tested participants' understanding of the relative magnitudes of different units (e.g., knowledge that a century is longer than a week).

4a. Unit magnitude comparison (distinct magnitudes; N=10): Participants were given the name of two units of measurement and asked to state which was the largest (e.g., centimetre or mile; decade or hour).

4b. Unit magnitude comparison (similar magnitudes; N=10): The instructions were identical to those used for Experiment 4a. However, this task was designed to be more difficult than 4a by using response options with more similar/comparable magnitudes (e.g. kilometre or mile; decade or year).

4c. Non-unit magnitude comparison (animal size) (N=15): Finally, we asked participants to make magnitude judgements about non-unit entities. The task involved pairs of animals drawn from the Size/Weight Attribute Test (Warrington and Crutch, 2007). Participants were presented with the names of two animals and asked to state which creature was the larger in terms of overall size (e.g. turkey or sparrow; salmon or shark). This task probed participants' ability to make magnitude-based judgements that did not involve measurement units.

3. Results

Mean and standard deviation scores for each group on each experimental task are shown in Table 2, together with significance values of pairwise comparisons between groups. Box and whisker plots showing the spread of the data in each group and experiment can be found in the Supplementary Material.

3.1 Experiment 1

The performance of PCA and tAD patients did not differ significantly on any of the three tasks included in Experiment 1. In comparison to controls, PCA patients only showed impaired performance on the dimension matched condition (1b, on which controls achieved near ceiling scores). tAD patients scored significantly below controls on both unit tasks (1a and 1b). However, neither patient group was significantly impaired on the control, non-unit semantic judgement task (1c), suggesting that no generic short-term memory, comprehension or other deficits could account for impaired performance on the other 2-AFC tasks administered in this study.

Across all participants, response accuracy was lower when the dimension of measurement was not matched (1a) than when matched (1b; 1-tailed t-test: $t=4.97$, $P<0.001$). This difficulty effect was evident in all participant groups and reached significance in the larger tAD and control samples (PCA: $t=0.88$, $P=0.20$; tAD: $t=4.30$, $P<0.001$; Controls: $t=4.17$, $P=0.001$).

3.2 Experiment 2

In contrast to Experiment 1 which examined basic 'is it a unit' knowledge, PCA patients did score more poorly than tAD patients on Experiment 2's tests of the specific dimension of measurement to which unit terms referred. This PCA impairment relative to tAD was significant for the task of explicitly matching a unit term to the name of the relevant dimension (2b) and constituted a trend (*p*

= 0.053) for the task of pairing terms which relate to the same dimension (2a). PCA and tAD performance on both tasks was significantly impaired relative to controls.

3.3 Experiment 3

PCA patients also scored significantly lower than tAD patients on tasks tapping associations between unit terms and the real-world entities they are used to measure. The impairment in PCA relative to tAD performance was observed whether the question was framed in terms of the unit term (3a; e.g. “Which [of these things] would you measure in kilograms?) or an example object or substance (3b; e.g. “What units would you use to measure medicine?”). PCA scores were also significantly lower than those of controls on both these tasks. By contrast, tAD patients only showed impairment relative to controls when the question was framed in terms of the unit (3a).

3.4 Experiment 4

On tasks tapping a more specific comparison of magnitudes conveyed by particular units of measurement, PCA patients scored significantly lower than tAD patients for units with distinct magnitudes (4a) and showed a trend for lower scores for units with more comparable magnitudes (4b). PCA patients were also significantly worse than tAD patients on a non-unit task requiring the size comparison of different animals (4c), suggesting that they also had greater impairment in magnitude processing where units were not involved. Relative to controls, these differences were significant for the animal size comparison task and showed a trend in comparable unit magnitudes task for the PCA patients, whilst tAD-control differences reached significance for the comparable unit magnitudes task and showed trends in the remaining tasks.

4. Discussion

This study compared verbal knowledge of measurement unit terms in individuals with PCA, a typical AD patient control group and a group of healthy controls. PCA patients did not differ significantly from tAD in the two tests tapping fundamental (superordinate) knowledge that a given term was a measurement unit, and importantly showed relatively preserved non-magnitude semantic knowledge relative to healthy controls on a comprehension test involving non-unit terms (Experiment 1). They did, however, achieve lower scores than tAD patients on a series of tests tapping more fine-grained unit knowledge regarding the dimension to which units refer, the entities measured with given units and the approximate magnitude of units (Experiments 2-4; significant differences in 5/7 tests, strong trends in the remaining two tests). Among this set of tasks tapping more detailed knowledge of measurement units, the only pair of tests on which the lower PCA performance level did not differ significantly from that of healthy controls were the two approximate magnitude tests ("Which is larger…?"), though control performance was at or near ceiling on these tasks. Overall, tAD patients showed an intermediate profile of performance, numerically superior to PCA and inferior to controls on every task. Like PCA patients, tAD patients did not differ significantly from healthy controls on the non-magnitude comprehension task (1c). The only other task on which tAD patients did not show at least a trend towards worse performance than controls was in their everyday knowledge of the units used to measure given entities (3b).

Several plausible explanations may arise from these results. We hypothesised that PCA patients, with pronounced parietal but limited anterior temporal lobe atrophy, would show a gradient of performance with impaired magnitude-dependent knowledge but relative sparing of more purely verbal knowledge of measure unit terms. We found that the patients did indeed show least impairment for superordinate unit knowledge (Expt 1) but were impaired for magnitude-based unit judgements (Expt 4). However, they also had substantial problems in relating units to real world objects (Expt 3) and to the dimensions to which they pertain (Expt 2). By contrast, the typical AD patient control group, with more comparable temporal and parietal atrophy, showed a more equivalent pattern of weakening in their magnitude and non-magnitude knowledge for measurement units. A limitation to these findings is the fact that the PCA and tAD groups were not matched for severity beyond disease duration, which may be an unsuitable variable due to the lack of correspondence in the course of progression of PCA and tAD, and on the other hand, the lack of dissociation in favour of the PCA for some tasks (performing better than the tAD). Another variable that might influence the interpretation of the results is the larger sample size of the tAD group, which might render larger significant effects in the tAD group. Finally, level of education varied across the PCA and tAD group in particular, with lower levels of academic attainment in the PCA group, which might make more difficult for this group to handle magnitude measures.

4.1 Anatomical considerations

Naturally the pattern of cognitive performance on the experimental tasks reflects the pattern of atrophy in these patients. Although no imaging was available for either diagnostic group in this study, previous studies using structural MRI to compare PCA and tAD patients have revealed significantly thinner cortex predominantly in the right superior parietal lobe in PCA and significantly greater thinning in the left entorhinal cortex in tAD (Lehmann et al., 2011). In the regions argued to be most critical to underpinning verbal semantic knowledge (anterior temporal lobe [ATL]; Patterson et al., 2007) and numerical semantic knowledge (inferior parietal cortex; Dehaene et al., 2003), Lehmann et al. (2011) did not find significant differences between PCA and tAD but did reveal (i) percentage differences in the same direction (right inferior parietal cortex 5-10% thinner in PCA than tAD; left ATL 5-10% thinner in tAD than PCA) and (ii) significant reductions in thickness in the inferior parietal and ATL cortices in both PCA and tAD groups relative to healthy controls. Thus whilst the atrophy pattern in PCA is less focal than that observed in some neurodegenerative conditions such as semantic dementia (Chan et al., 2001; Galton et al., 2001), the available neuroimaging evidence would predict a greater impairment of numerical than non-numerical semantic knowledge, as has been demonstrated in previous studies (Delazer et al., 2006; Kas et al., 2011) . In the present study, we found PCA patients also exhibit deficits in non-numerical knowledge of measurement units. One possible explanation would be that thepoor performance of PCA patients on Experiments 2-4 of the current study reflect a role for degraded parietally-mediated magnitude and number systems in supporting unit knowledge, whilst the relatively spared performance on superordinate unit knowledge tests (1a and 1b) and especially non-magnitude comprehension test (1c) reflects relative sparing of ATL-mediated (non-numerical) conceptual representations. However, the significant overlap in performances between the tAD and PCA groups may, contrary to the argument above, also point towards a further involvement of damaged semantic areas in PCA.

Whilst we are unaware of any previous studies specifically examining comprehension of measurement units, two previous studies have indicated parietal involvement in the comprehension of words that are closely associated to number processing but that do not themselves label specific magnitudes. Delazer and Benke (1997) reported patient JG who lost conceptual understanding of arithmetic operations and principles following surgery for a left parietal tumour. Delazer et al (2006) also reported the PCA patient HR who exhibited loss of arithmetic principles in addition to a broader impairment of number calculation, manipulation, estimation and fact retrieval. Thus, the suggestion that PCA patients have difficulty comprehending measurement unit terms, which are related to but do not explicitly reference numbers, is novel but nonetheless consistent with previous research findings.

4.2 Cognitive considerations

If one accepts that premise that PCA patients show impaired subordinate knowledge for measurement unit terms owing primarily to disruption of parietal mechanisms, we must consider the nature of the cognitive representations which normally support such understanding. The triple code model

(Dehaene, 1992; Dehaene and Cohen, 1995) proposes three representational codes for the representation of numbers: (i) an analogical quantity or magnitude code representing numbers on an oriented number line and constituting semantic knowledge of proximity and relative magnitude, (ii) a verbal code representing numbers as a parsed sequence of words and central to accessing rote verbal knowledge of arithmetic facts, and (iii) an Arabic code for the representation and manipulation of Arabic number strings and employed for transcoding, multi-digit operations and parity judgements.

One possibility is that different aspects of our knowledge about measurement units are (differentially) supported by these different representational codes. Knowledge of approximate (comparative) magnitude (e.g. knowing a tonne is ‘more’ [heavier] than a kilogram) might be represented primarily within the analogical magnitude code, whilst precise magnitude (e.g. a tonne equals 1000 kilograms, 1 foot equals 12 inches) might be represented primarily within the verbal code as a quantity ‘fact’. It is possible that the Arabic code might play a role in transcoding the regularities of the metric system (e.g. knowledge that the prefix ‘k’ equates to 1000 of the subsequent unit, i.e. 1kg = 1000g, 1km = 1000m), although if restricted to processing Arabic numerals this function might have to be achieved in conjunction with the (alphabetic) visual word form system. Less clear is the contribution that the three codes might make to more superordinate verbal knowledge that units are ‘measuring’ words or more associative information about the entities typically measured with certain units. However, just as the triple code system envisages certain numerical and arithmetic functions as being supported by multiple codes (even if one code is primary; Dehaene and Cohen, 1995), so it may be that one or more of these codes contributes to the representation of knowledge which is primarily coded within a dissociated verbal semantic system. This input might equate to a form of numerical/magnitude coding or tuning of the semantic representations of certain words (see below).

4.3 Where numbers meet words

One motivation in planning our examination of measurement unit comprehension in PCA was to move beyond previous evidence for the dissociation of numerical and non-numerical semantics, and instead ask how these systems communicate with and influence one another. From their work with semantic dementia patients who show focal ATL degeneration, Julien et al. (2010) have claimed that the temporal lobes may contribute to the representation of precise quantity knowledge (typically regarded as a parietally-mediated form of knowledge). Although our data does not unequivocally support this notion, a possible interpretation might mirror this position: we argue from our work with PCA patients who show prominent parietal atrophy, that the parietal lobes might contribute to the conceptual representation of unit of measurement terms, although in our case, the role of other semantic-related areas and the confounding factor of unmatched/dissociated samples, are also plausible explanations. The idea in support of the role of the parietal lobe is compatible with the previous finding that, in individuals with semantic dementia, quantifiers (words such as ‘many’ and ‘few’) tend to pattern more with numerical than linguistic concepts (Cappelletti et al., 2006).

The present argument that parietal magnitude and number representations contribute to our fundamental understanding of measurement unit terms is not the first suggestion that higher order parietal representations influence verbal semantic knowledge. It has previously been argued that semantic representations of geographical place names (e.g. America, Cornwall) are spatially coded, that is fundamentally linked to ego- and allocentric representations of the actual geographical location and other spatial concepts (e.g. ‘west’; Crutch and Warrington, 2003, 2010; see also Hoffman & Crutch, 2016). Such work also builds on a rich tradition of linguistic studies of the nature of spatial influences on language (see Chatterjee, 2001, 2010 for reviews). Together with the present data, such claims relate to a broader notion that beyond the sensorimotor channels traditionally implicated in the acquisition and representation of concrete concepts (see Patterson et al., 2007; Mahon and Caramazza, 2008; Barsalou, 1999), a host of additional primary brain systems influence the formation of conceptual knowledge, particularly for abstract words (Crutch et al., 2012, 2013; Troche et al., 2014). Examples here include the role of magnitude information in concepts such as 'amount' and 'length', the role of time in concepts such as 'moment', 'instance' and 'history' (Crutch et al., 2013), which might be expected to be supported by parietal systems representing quantity in space and time. Another example is the more established claim of the importance of emotion information in the acquisition of abstract terms (Andrews et al., 2009; Kousta et al., 2009, 2011).

4.4 Conclusions

A sound understanding of measurement units' subordinate features (e.g. magnitude and relation to other measures of the same physical dimension) is critical in many fields of endeavour, as demonstrated disastrously when the NASA Mars Climate Orbiter was accidentally destroyed in September 1999 owing to miscommunications between computer programs employing different units for measuring force (newtons versus pounds; NASA, 1999). In more mundane, terrestrial contexts, measurement units remain highly useful concepts that facilitate many of our interactions with the world around us. The current experiments have highlighted the loss of this detailed measurement unit knowledge in individuals with the neurodegenerative syndrome PCA and provided an opportunity to explore the territory linking human verbal and numerical semantic systems. The challenge remains to elucidate exactly how numerical, magnitude, spatial and other higher order forms of parietal representation are transformed and combined to shape the meaning of certain words in our vocabulary. The present work may serve to confirm unit of measurement terms as relevant verbal carriers of magnitude and numerical information for future investigation of these questions.

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Table 1. Demographic information for each group and scores on neuropsychological assessments

	PCA (N=8)		tAD (N=21)		Controls (N=18)				
	Mean	*(SD)*	Mean	*(SD)*	Mean	*(SD)*	PCA vs tAD	PCA vs controls	tAD vs controls
Age	68.3	*(3.9)*	63.0	*(4)*	59.8	*(4.1)*	<0.01[a]	<0.001[a]	<0.01[a]
Age at onset	64.0	*(4.3)*	58.3	*(4.4)*	-	*(-)*	<0.01[a]	-	-
Gender (m/f)	5/3		11/9		9/9				
Education (years of)									
University (19 y)	0		6		2				
A-levels (14 y)	2		9		2				
Basic school (9 y)	1		5		14				
Read and write (1 y)	5		1		0				
Disease duration	4.4	*(2.5)*	4.7	*(2.3)*	0.0	*(0)*	>0.3[a]	-	-
MMSE (/30)	16.9	*(4.3)*	21.2	*(5)*	28.3	*(1.6)*	>0.1[b]	<0.001[c]	<0.001[c]
Immediate recall (/48)	9.9	*(8.1)*	11.2	*(8.7)*	29.1	*(4.7)*	>0.9[b]	<0.001[c]	<0.001[c]
Delayed recall (/12)	0.5	*(1.1)*	0.7	*(1.2)*	6.1	*(2.7)*	>0.6[b]	0.001[c]	<0.001[c]
Delayed recognition (/24)	14.5	*(2.6)*	15.7	*(3.8)*	22.8	*(1.5)*	>0.8[b]	<0.001[c]	<0.001[c]
Digits forwards (/9)	4.3	*(1.3)*	4.4	*(1.4)*	5.3*	*(0.9)*	>0.8[b]	>0.4[c]	>0.1[c]
Digits backwards (/8)	1.8	*(0.7)*	2.5	*(1.3)*	3.3*	*(0.5)*	>0.1[b]	<0.001[c]	0.038[c]
Phonemic fluency	9.9	*(6.8)*	15.8	*(8.7)*	26.6	*(9.3)*	>0.2[b]	0.008[c]	0.002[c]
Semantic fluency	5.0	*(2.6)*	8.3	*(3.4)*	16.1	*(3.7)*	>0.1[b]	<0.001[c]	<0.001[c]
Calculation	8.1	*(5.6)*	15.2	*(4.4)*	-	-	0.021[b]	-	-
VOSP Shape detection (/20)	12.4	*(7.3)*	19.5	*(0.7)*	-	-	<0.001[b]	-	-
VOSP Fragmented letters (/20)	2.4	*(2.6)*	17.7	*(2.7)*	-	-	<0.001[b]	-	-
VOSP Object decision (/20)	5.4	*(4.2)*	13.9	*(2.4)*	-	-	<0.001[b]	-	-
VOSP Dot counting (/10)	3.5	*(2.7)*	9.9	*(0.2)*	-	-	<0.001[b]	-	-
VOSP Position discrimination (/20)	9.6	*(3.7)*	18.3	*(4)*	-	-	<0.001[b]	-	-
VOSP Number location (/10)	1.1	*(2.1)*	7.7	*(1.9)*	-	-	<0.001[b]	-	-
VOSP Cube analysis (/10)	1.5	*(2.3)*	8.6	*(1.6)*	-	-	<0.001[b]	-	-

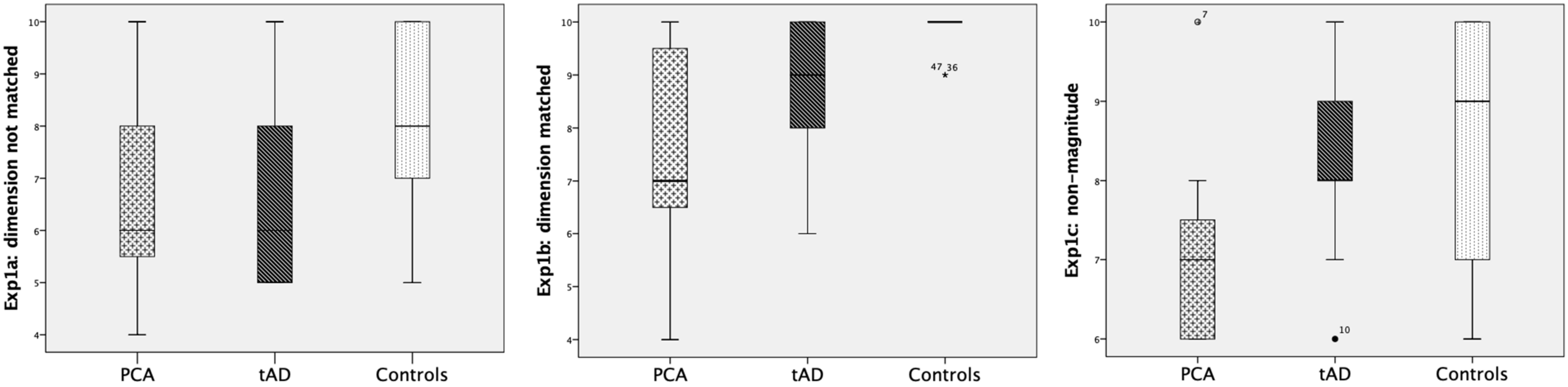
P-values of pairwise group comparisons; highlighted cells indicate comparisons reaching formal significance levels (P<0.05)
*N=11
[a]t-test (one-tailed)
[b]Regression covarying for age and disease duration
cRegression covarying for age

Table 2. Performance on tasks probing different aspects of unit knowledge

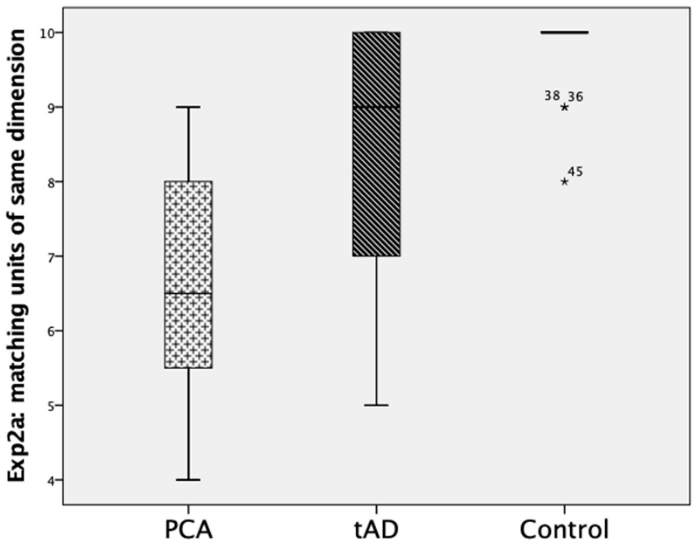
	PCA Mean	PCA *(SD)*	tAD Mean	tAD *(SD)*	Control Mean	Control *(SD)*	PCA vs tAD[a]	PCA vs control[b]	tAD vs control[b]
1. Knowledge that target is a unit									
a. Dimension not matched /10	6.6	*(1.9)*	6.9	*(1.7)*	8.2	*(1.7)*	>0.4	>0.2	0.02
b. Dimension matched /10	7.5	*(2.1)*	8.8	*(1.1)*	9.8	*(0.4)*	>0.1	0.021	0.002
c. Non-magnitude (person adjectives) /10	7.1	*(1.4)*	8.3	*(1.1)*	8.5	*(1.3)*	>0.1	>0.3	>0.7
2. Dimension to which unit refers									
a. Matching units of same dimension /10	6.6	*(1.8)*	8.4	*(1.7)*	9.7	*(0.6)*	0.053	0.001	0.008
b. Matching unit to dimension name /10	7.0	*(2.2)*	9.4	*(1)*	10.0	*(0)*	0.003	0.002	0.014
3. Entities measured and units used									
a. Entity measured with given unit /10	7.3	*(2)*	9.2	*(1.5)*	9.9	*(0.3)*	0.006	0.006	0.032
b. Unit used to measure given entity /10	8.0	*(1.4)*	9.2	*(1.1)*	9.7	*(0.6)*	0.033	0.008	>0.1
4. Approximate magnitude of a unit									
a. Unit magnitude (distinct) /10	8.3	*(1.6)*	9.4	*(1)*	9.7	*(0.5)*	0.029	>0.1	0.062
b. Unit magnitude (similar) /10	8.0	*(2)*	9.0	*(1.1)*	10.0	*(1.3)*	0.075	0.064	0.044
c. Non-unit magnitudes (animal size) /15	13.1	*(1.8)*	14.7	*(0.6)*	15.0	*(0)*	0.023	0.03	0.072

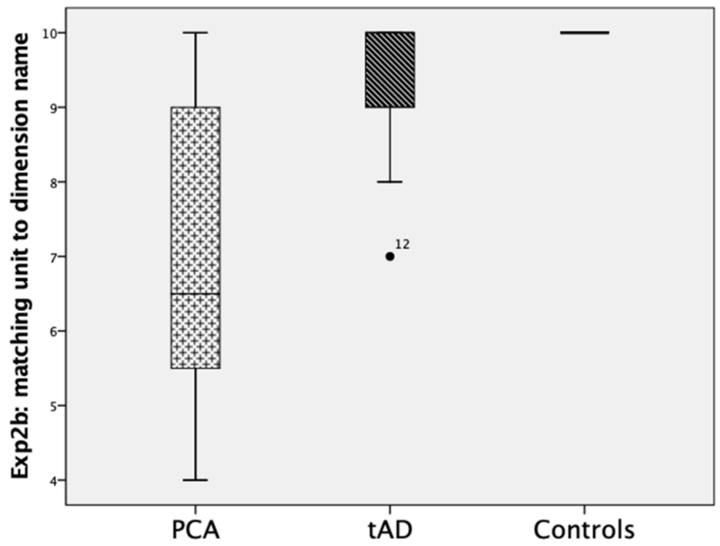
P-values of pairwise group comparisons; highlighted cells indicate comparisons reaching formal significance levels ($P<0.05$)
[a]Regression covarying for age and disease duration
[b]Regression covarying for age

Experiment 1

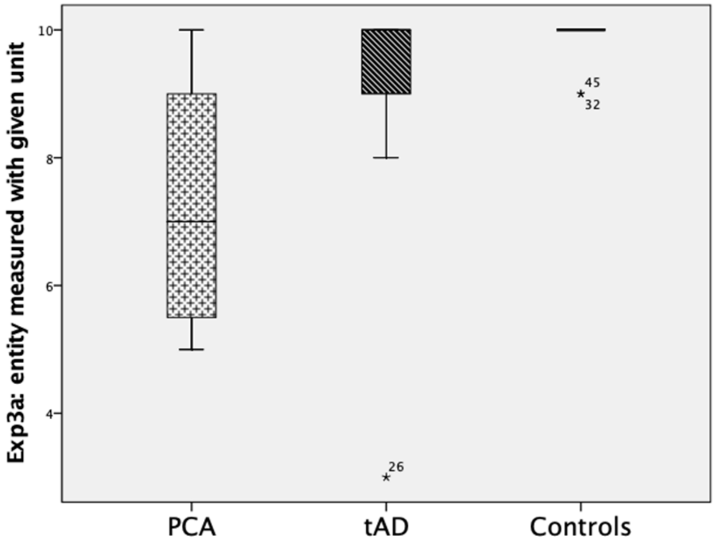


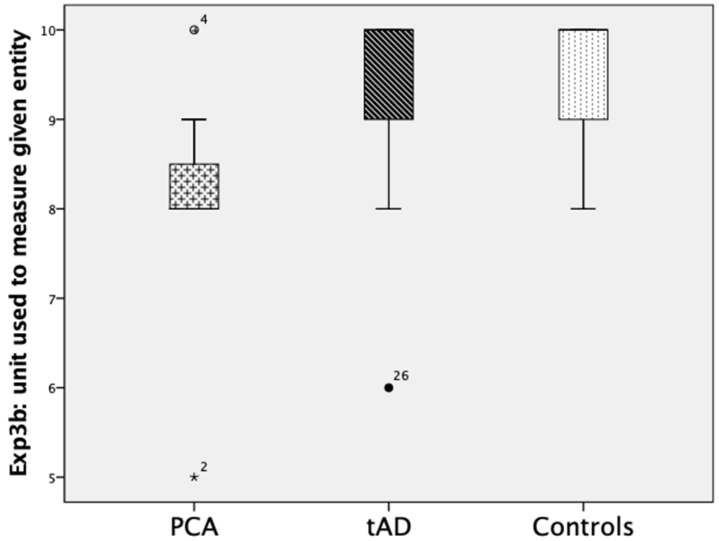
Experiment 2





Experiment 3





Experiment 4